RESULTS OF REMOTE SOUNDING OF THE ATMOSPHERE AND OCEAN IN THE INFRARED AND MICROWAVE REGIONS ON THE 13th VOYAGE OF THE SCIENTIFIC RESEARCH VESSEL "ACADEMICIAN KURCHATOV"

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An experimental study of the thermal radiation of the atmosphere and sea surface was performed aboard a vessel in the Atlantic Ocean from 57°N to 20°S from June through September 1972 in the infrared (IR) and microwave (MW) ranges in the following spectral intervals: /1*

IR range — radiometers in the 8, 11, 13 and 15 micron spectral ranges.
— spectrometer, in the 10-15 micron range.

MW range — in the 0.8, 1.35, 1.6, 2.5, 3.4 and 8.5 cm ranges.

These measurements were accompanied by photography of the water surface by means of a semiautomatic camera and recording of the reflected solar radiation by means of a photometer in the 0.4-0.7 micron range.

1.1. Apparatus and Methods of Measurement in the IR Range.

The radiation method of measuring the surface water temperature (S.W.T.) is widely used because it allows remote determination of the thermal regime of the surface layer of the water with various scales of spatial resolution from [Translator's Note: blurred] meters to kilometers with observations from aircraft and satellites. Experiments aboard the "Kosmos-149, 243, 320 and 384" /2
satellites have shown in particular that the mean square deviation of the radiation temperature T_r determined on the basis of satellite measurements from the kinetic water temperature T_w, measured from ships by the contact method employing thermoresistors is at least 2°C [1]. Measurements of the thermal radiation of the surface of the water in the IR range were performed to determine the role of temperature variations in the surface layer of the ocean T_w on changes in the radiation temperature [Translator's Note: omission].

*Numbers in the margin indicate pagination in the foreign text.

For this purpose, a radiometer was used whose optical system was described in [2], having a spectral sensitivity in the 10-12 micron range and a visual field measuring 2 × 4°. The sensitivity of the radiometer was checked using a black radiator at air temperature and at the temperature of melting ice. A conical black body with a temperature of 40°C was used as a reference radiator. The mean square random error in the measurements was 0.15°C. When converted to an absolute energy scale, the possible error is 0.25°C.

Measurements of the intensity of the radiation of the water surface were carried out with a stabilized gyro platform. The measurements were performed at an angle of α = 0-55° to the horizon.

The kinetic temperature of the water was measured with an electrothermometer, mounted on a buoy, floating on the lee side at a distance of about 2 m from the side of the ship, at a depth of 5 cm. In comparing the radiation and kinetic temperatures, we also use data on water temperature measured with a mercury thermometer by the members of the meteorological section aboard the ship.

1.2. Relationship Between Radiation and Kinetic Temperature. /3

An example of the comparison of the radiation temperature T_r and the kinetic temperature T_w for measurements at an angle of α = -45° is shown in Figure 1. The mean difference is -0.55°C. The observed differences lie within limits of -1.5°C to values of 0.9°C, observed under conditions of a nearly total term during the noon hour. A comparison of the temperature difference δT with the wind speed, difference in the temperatures of water and air, shows no noticeable correlation. The difference δT is probably formed under the influence of many meteorological factors and therefore may be viewed as a random value, whose probability density distribution is characterized by statistical moments. For the data shown in Figure 1, the mean square deviation of the temperature σ_t = 0.2°C, the asymmetry A = 0.08 and the excess E_x = 0.13.

Choice of the angle α = -45° at which the relationship between temperatures T_r and T_w is considered, is based on the fact that T_r begins to decrease rapidly as the horizon is approached. The mean path and scatter of values for T_r for 11 days of measurements under various meteorological conditions is shown in Figure 2. The average decrease in the radiation temperature at angles

$\alpha = -2°C - -45°$ is 3.2°C. With an increase in $|\alpha|$ from 45° to 55°, the average increase in T_r, as indicated by an analysis of the measurements, amounts to 0.15°C. To estimate the temperature pattern for T_r at angles α from -55° to -90°, let us use the data from [3], from which it follows that at $|\alpha| > 45°$ the radiation of the water surface when the latter is agitated shows practically no /4 difference (within limits of accuracy of 0.1°C) from the radiation pattern of a flat surface, determined by Fresnel reflection. Corresponding calculations using the coefficients of radiation of the water taken from [4] indicate that an increase in the radiation temperature angles $\alpha = -55°$-90° with an average radiation intensity of the atmosphere from the zenith looks like $\overline{I} = 0.55$ mW/cm^2 ster. • μ and does not exceed 15°C. Hence, with observations at the nadir the mean difference $\delta T = T_r - T_w$ is estimated to be -0.25°C.

If it is desired to determine the radiating capacity of the ocean-atmosphere system as the ratio of the measured intensity of the radiation $I\Delta\nu(\alpha)$, being the sum of the radiation of the water and the reflected back radiation of the atmosphere, to the intensity of the radiation according to Planck at a water temperature of T_w, on the basis of the results of the present measurements $\tilde{\varepsilon}(\alpha = -45°) = 0.992$, while for the angle $\alpha = -90°$ $\tilde{\varepsilon} = 0.996$ in accordance with the differential $\delta T = 0.25°C$.

Inasmuch as the calculation of the radiating capacity uses the kinetic temperature of the water T_w, measured not at the surface of the water but at some depths, it is necessary to take into account the additional error due to the vertical gradients of the temperature in the water. It is possible to determine T_w as the limit $T_w = \lim_{z \to 0} T(Z)$ where Z is the thickness of the water layer from the level of the horizon. The measurements of the temperature profile of the water with depth in the Atlantic Ocean for the summer period at latitudes of 40-55°N give values for the gradients of 0.1°C maximum in the layer from 0.1 to 5 cm with waves having a scale value of 4. The stability of the temperature gradient in this connection has to do with the existence of a /5 surface film. Hence, the possibility of a temperature gradient of 0.1° in the layer down to 5 cm leads to an additional error in the radiating capacity of ±0.0013, which gives us $\tilde{\varepsilon}(\alpha = -45°) = 0.992 \pm 0.007$.

Upon comparing these results with the data for measurements performed by other authors, it is necessary to take into account the difference in the spectral intervals, the methods of calibration and the meteorological conditions.

For example, measurements in the North Atlantic Ocean using a radiometer in the spectral region from 8 to 12 microns and calibrating the instrument with water for the direction $\alpha = -90°$ gives a maximum for the temperature differential distribution probability of $\delta T = -0.2°C$ for latitudes 55-60°N and $+0.2°C$ for latitudes 40-55°N [5, 6]. If we take into account the difference in the radiating capacity of the water used in [5] as the reference source, from 1, this leads to a displacement of the difference δT toward lower temperatures and the cited results practically will be similar on the average (with an accuracy up to the measurement error) to the value obtained of $\delta T = 0.25°C$.

1.3. Angular Pattern of Radiation of the Water Surface.

Measurements of the angular pattern of the radiation from the water were carried out at angle interval $\delta\alpha = 2°$ within the limits of angles from 0° to -10° and at angles $\alpha = -15°$, -20°, -30°, -45° and -55°. Their distance from the side of the ship to the center of the sighted area varied from 12 m at $\alpha = -45°$ to 500 m at $\alpha = -2°$.

In the example of the angular pattern of radiation shown in Figure 2, a common feature of all of the sections is the nearly monotonic decrease in the radiation intensity with decreasing distance to the surface of the water, which is characteristic for cases of cloud cover with low clouds in the scanning direction. /6

The two-degree angular resolution of the radiometer made it possible to discern "warming" near the surface of the water at angles $\alpha = -6° - -2°$, observed in the cases of a cloudless sky.

The angular dependence of the radiation $I\delta\nu(\alpha)$ may be used to determine the radiating capacity of the water surface. The radiation intensity $I\delta\nu(\alpha)$, incident on the input of the device, may be represented in the form

$$I\Delta\nu(\alpha) = B\Delta\nu(T_a)[1 - \tau(\alpha)] + I'_\alpha \tau(\alpha) \tag{1}$$

where $\tau(\alpha)$ is the transmission function of the layer of the atmosphere $l(\alpha)$ from the center of the sighted area to the device, $B\delta\nu(Ta)$ is the intensity of the radiation according to Planck in the frequency interval $\delta\nu$ of the spectral sensitivity of the device, T_a is the water temperature, I'_α is the radiation intensity of the surface of the ocean, including the intrinsic radiation of the water at a temperature T_w and the reflected back radiation of the atmosphere.

The intensity of the radiation of the surface of the ocean when waves are present I'_α can be represented in the following form [3, 7, 8]:

$$I'_\alpha = \frac{S(\alpha)}{\sin\alpha} \int_{\infty}^{\infty} \int_{\tan\alpha}^{\infty} \left\{B(T_w) - r(w)[B(T_w) - I'(\mu)]\right\} \frac{\cos\omega}{\cos\beta} P(Z_x, Z_y) dZ_x dZ_y$$

where $B(T_w)$ is the radiation intensity according to Planck at a water temperature of T_w: $r(w)$ is the coefficient of reflection of the water according to Fresnel at an angle of incidence w: $I'(\mu)$ is the intensity of the back radiation of the atmosphere; β is the angle of inclination of the area of the water surface with respect to the horizon, having slopes of $Z_x \pm \delta Z_x/2$ and $Z_y + \delta Z_y/2$ along the x and y axes to the plane of the horizon; P is the probability of slopes Z_x, Z_y per unit of water surface; $S(\alpha)$ is the "blackout" function, which considers the shielding of the crests of the waves by other parts of the surface and is determined on the basis of equation (2) from the condition $r(w) = 0$ and $I'(\alpha) = B(T_w)$. From the values that are incorporated in the equations (1) and (2), temperatures T_a and T_w are measured and the intensity of the radiation of the atmosphere $I'(\mu)$. The transmission function of the atmosphere $\tau(\alpha)$ is approximated by the exponential function $\tau(\alpha) = \exp[-kal(\alpha)]$ where a is the density of water vapor, k is the coefficient of absorption of water vapor, assumed to be equal to 0.15 cm^2 per gram. The intensity I'_α is determined from (1) on the basis of the measured intensity $I\delta\nu(\alpha)$. Hence, there is a theoretical possibility of determining the probability of slopes $T(Z_x, Z_y)$ on a basis of the system of equations (2) for different angles also. However, this problem is incorrect in the sense that comparatively small errors in measurement of I'_α and errors in stating the kernel of the equation in which coefficient of reflection $r(w)$ is included can lead to significant errors in determining /7

$P(Z_x, Z_y)$. As a matter of fact, the function r(w) is determined by the law of reflection of Fresnel only in the condition that there is no foam on the surface of the water. In addition, it is difficult in practice to obtain the distribution of intensity $I'(\mu)$ for the entire sky. Therefore, in [3, 7, 8] they are limited to the assumption that the intensity $I'(\mu)$ is independent of azimuth, the foam on the surface is not taken into account, and the probability of slopes $P(Z_x, Z_y)$ takes the form of a normal Gaussian distribution, while the problem boils down to finding the mean square deviation $\sigma = \sigma_x = \sigma_y$, characterizing the distribution P: /8

$$P = \frac{1}{2\pi\sigma^e} \exp\left[-\frac{Z_x^2 + Z_y^2}{2\sigma^e}\right] \tag{3}$$

Another approach is possible. Inasmuch as the linear dimensions of the sighted area when viewed at angles close to the horizon are comparative to the mean wavelength $\bar{\lambda}$, the time-averaged fluctuations in the intensity $I\delta\nu(\alpha)$, the surface of the water may be considered flat with an unknown coefficient of reflection $R'(\alpha) = 1 - \varepsilon'(\alpha)$, where $\varepsilon'(\alpha)$ is the radiating capacity. Then equations (1) and (2) can be rewritten as follows:

$$\bar{I}\Delta\nu(\alpha) = \varepsilon'(\alpha)B(T_w)\,\tau(\alpha) + B\Delta\nu(T_a)[1 - \tau(\alpha)] + [1 - \varepsilon'(\alpha)]I_\alpha\tau(\alpha) \tag{4}$$

Hence, the radiated capacity $\varepsilon'(\alpha)$ is determined as follows:

$$\varepsilon'(\alpha) = \frac{I_\alpha - B\Delta\nu(T_a) + [B\Delta\nu(T_a) - I_\alpha]\tau(\alpha)}{\tau(\alpha)[B\Delta\nu(T_w) - I_\alpha]} \tag{5}$$

The difference between $r'(\alpha)$ and the value $r'(w)$, determined by the Fresnel formulas, will characterize the degree of agitation of the surface of the water by waves. /9

1.4. Determination of the Radiating Capacity.

Let us examine the preliminary results and measurements of the angular pattern of radiation for cases of waves measuring 1 to 4 on the scale. The average value of the effective radiating capacity of the surface of the water $\tilde{\varepsilon}\alpha$ with a cloudless sky in the scanning direction are shown in Tables 1 to 4. These same tables also give the average values of the radiating capacity of the ocean-atmosphere system $\tilde{\varepsilon}_1(\alpha) = \frac{I\Delta\nu}{\beta\Delta\nu(T_w)}$ for the cases of a cloud-free sky and $\tilde{\varepsilon}_2(\alpha)$ averaged for cloudy and cloudless cases. A comparison yields the radiating capacity $\varepsilon(\alpha)$ for a calm water surface on the basis of the data in [4]. Note that a characteristic feature of the angular pattern $\varepsilon'(\alpha)$ is an increase in the values near the horizon corresponding to the above mentioned "warming". It is possible that this increase is the result of the angles formed by the waves as well as the increased influence of the foam at angles close to the horizon, inasmuch as the probability of the location of foam on the crests of the waves is higher than in the troughs. It is clear in Table 1 that the values $\tilde{\varepsilon}(\alpha) >$ $> \varepsilon'(\alpha) > \varepsilon(\alpha)$, which is the result of the contribution of the reflected radiation from the sky to the radiation of the ocean. The average values obtained for $\tilde{\varepsilon}(\alpha)$ and $\varepsilon'(\alpha)$ may be used for interpretation of the data from remote measurements from aircraft and satellites, with angular scanning above the surface of the water.

We shall now consider the possibilities of determining the mean square slopes σ, which proceed from equation (2). Figure 3 and Figure 4 show examples of the angular pattern of the ratio of measured intensity of radiation from the surface of the water $I\Delta\nu$ to the radiation intensity at B at a water temperature T_w compared with the angular dependencies of the radiation calculated according to formula (4) for now reflection and according to (2) for one dimensional normal Gaussian distribution of probability of slopes $P = 1/\sqrt{\alpha\pi}\,\sigma$ $\exp(-Z_x^2/\alpha\delta^e)$. One dimensional distribution has been used because on the basis of data from meteorological observations for these cases, wind direction and swells are similar. It is clear from Figures 3 and 4 that the measured and calculated intensities decrease monotonically, to an angle $\alpha = -10°$, while at angles from $-6°$ to $2°$ the experimental values increase toward the horizon, as was noted above and which can be explained by an increase in the curvature of the waves at the crests in comparison with the average curvature of the waves. Hence, a comparison of the experimental and calculated values for the purpose of estimating the mean square slopes σ can be performed advantageously at α = 8 to 10°, and for the cases shown in Figure 3 and 4 the values σ describing the experimental curves $I\Delta\nu/B(T_w)$ amounts to 0.1 and 0.18, respectively. /10 (angles β = 6 and 10°). These estimates, taking into account a wind speed of 2 and 6 meters per second, agree with the data in [3], and also with the average slopes of the trochoidal waves which are 6-16° with ratios of 0.05 to 0.14 between the height and length of the waves. Examples given indicate the possibility of using the radiation from the ocean in the spectral region from 10 to 12 microns for estimating the mean square slopes.

Let us summarize briefly the principal results:

1. A comparison has been performed of the radiation T_r and kinetic T_w temperatures of the surface layer of the water on the basis of measurements made in the lee of the vessel. The main difference $\overline{\delta T} = \overline{T_r - T_w}$ is -0.55°C with measurements at an angle α = -45° to the horizon with a mean square deviation of 0.2°C. The average difference $\overline{\delta T}$ at α = -90° is estimated to be -0.25°C.

2. On the basis of the angular pattern of radiation of the water surface, the angular dependence of the effective radiating capacity of the ocean-atmosphere system $\varepsilon(\alpha)$ has been determined as well as the radiating capacity of the surface of the water $\varepsilon'(\alpha)$ with consideration of the reflected radiation of the atmosphere. $\varepsilon'(\alpha)$ is characterized by an increase at angles close to the horizon.

3. Results are presented from an estimate of the mean square angles of the slopes of the waves for cloudless conditions, supporting the possibility of using measurements of the intrinsic radiation of the ocean for determining the characteristics of the waves.

2.1. Apparatus and Methods of Measurement in the Microwave Region. /12

The radiometric apparatus intended for performing measurements of microwave radiation from the atmosphere and surface of the ocean consisted of 5 autonomous radiometers covering the range from 0.8 to 8.5 cm. The 2.5 cm radiometer could be adapted to the 3.4 cm wavelength by exchanging the input device.

The technical characteristics of the radiometers are shown in Table 2.1.

TABLE 2.1.

Characteristics	λ_1	λ_2	λ_3	$\lambda_4(\lambda_5)$	λ_6
Wavelength (cm)	0.8	1.35	1.6	2.5(3.4)	8.5
Fluctuation sensitivity (K/sec)	4	3	2	1(1)	1.5
Beamwidth at the 3 db level (degree)	4.5	4	4.5	3(4)	7.5
Coefficient of scattering	0.2	0.2	0.2	0.15(0.15)	0.2
Polarization[1]	l	l	l	$l(l)$	l, + e

[1]Symbols: l - linear; e - elliptical polarization.

Aboard the ship, the receiving antennas as well as the input devices of the radiometers for wavelength λ_1 to λ_5 were mounted coaxially on a gyro--stabilized platform on the right side on a tilting device (see Figure 5) which made possible sounding over a range of angles of ±45° azimuth and 90° to -70° altitude. The receiving antenna for wavelength λ_6 was mounted separately from the other antennas so that its beam was perpendicular to the side of the ship /13 and could be moved over a range of altitudes from +25° to -70°. The change in the plane of polarization of the receiving antennas was carried out mechanically by turning the antennas (λ_1-λ_5) and the radiator (λ_6) around their optical axes. The receivers of the radiometers and the recording apparatus were mounted in the laboratory and connected with the receiving antennas by a cable approximately 15 meters long.

The radiometers were calibrated using the intrinsic radiation from standard targets mounted on a special mast and on a bracket which was hinged to a folding platform on the side of the vessel on the boat deck. The standard targets were designed so that they constituted a mirror for radiowaves on the one hand on one side and a black body on the other; the temperature of this black body was measured by means of thermosensors.

The accompanying measurements included photography of the sea surface and determination of its albedo, and they were performed by means of semiautomatic cameras (type RFK-5) and two photometers working in the visible region of the spectrum (0.4-0.7 microns). The photometers and the camera were mounted coaxially with the receiving antennas of the radiometers on a single rotating device. Calibration of the photometers was carried out using the standard disc, which had an albedo of 68%.

The recording of the measurement results was carried out by means of a 7 channel magnetic recording unit which was intended for the input and processing of written information for computers and 5 strip-chart recorders (type EPP-09) intended for performing monitoring recordings and initial processing of the data obtained.

To investigate the angular characteristics of the radiation of the atmosphere and the sea surface the receiving antennas of all the radiometers were rotated simultaneously with respect to the altitude θ at 5 to 15° steps and at each position the radio brightness temperature $T_{rb\lambda}$ was measured at each position of the antennas for 0.5-1.5 minutes by all of the radiometers together. The angular sections were recorded as a rule with vertical and horizontal polarizations of the receiving antennas. The measuring time for each section for both polarizations was 30 minutes on the average, which made it possible in most cases to take into account the measurement conditions, considering them to be the same for the entire segment. /14

During the performance of the studies of the variations of radiation with time, the receiving antennas were immobilized and recording was carried out for 5 to 30 minutes. Approximately 1/4 of all of the measurements of the time variations $T_{b\lambda}$ were accompanied by recordings from the string wave recorder, mounted at the bow of the ship. The wave recorder was equipped with a device which made it possible to exclude the influence of the rolling of the ship on its readings.

The measurements of $T_{b\lambda}$ during the day, as a rule, were also accompanied by photometry and photography of the surface of the ocean.

2.2. Results of Microwave Measurements.

1. As an example of the angular distribution of the radio brightness temperature of the microwave radiation of the atmosphere and the surface of the

ocean $T_{b\lambda}(\theta)$, Figure 6 shows the data from measurements that were made on the 21st-22nd of July under 3.4 cm wavelength. The measurements were performed with a cloudless atmosphere and altocumulus fractured clouds, having practically no influence on the results of the measurements at this wavelength. The state of the surface of the ocean on the other hand changed during the time between the first and last measurements as indicated by the data from visual estimates and measurements of the wind speed from 0 to 3 points. /15

The absolute calibration of/the radiometers was performed at 2 points on the radiometric scale on the basis of the calculated radio brightness temperature of the atmosphere at the zenith ($\theta = 90°$) and $T_{b\lambda}$ measured by means of standard targets for the sea surface at $\theta = -60°$. The average values of the radio brightness temperatures and the corresponding mean square values for $\theta = 90°$, calculated on the basis of the data of radio sounding from aboard the vessel during the period of our measurements for cloudless and slightly cloudy atmosphere as shown in Table 2.2.

TABLE 2.2.

Parameters	λ cm					
	0.8	1.35	1.6	2.5	3.4	8.5
$T_{b\lambda}$ °K	38.0	84.3	29.0	7.22	5.32	3.15
$\sigma_{T_{b\lambda}}$ °K	4.4	12.3	4.15	0.90	0.55	0.35

Determination of $T_{b\lambda}$ at $\theta = -60°$ was carried out by means of the following expression:

$$T_{b\lambda}(-60°) = [1 - R_\lambda(-60°)]T_0 + R_\lambda(-60°)T_{b\lambda}(60°) \tag{2.1}$$

Where T_0 is the temperature of the sea surface, $T_{b\lambda}(60°) = T_{b\lambda}(90°)$ cosec 60°, $R_\lambda(-60°)$ is the coefficient of reflection of the surface of the water. The value T_0 was obtained on the basis of data from hydrometeorological measurements, $R_\lambda(-60°)$ was determined on the basis of data from measurements using standard targets with 6 antennas. /16

The accuracy of determination of the brightness temperature of the target ($T_{be} = A_e, T_e$) depends primarily on the measurement accuracy of A_e. The measurements that were performed at the Institute of Physics of the Atmosphere of the Academy of Sciences of the USSR by the method of comparing T_{be} with the brightness temperature of the radiation from the forest indicated that the error in determining T_{be} does not exceed 1 to 2%.

In those instances when $A_\lambda(-60°)$ was not measured, calibration of the radiometers was performed with $\theta = -40°$ with vertical polarization, and in this case according to the data from the calculations [9], experiment [10] and our measurements (see Figure 6) the radio brightness temperature is practically independent of the state of the sea surface. Calculation of $T_{b\lambda}(-40°)$ was performed on the basis of the formula for the analogous expression (2.1) while the values of the coefficients $A_\lambda(-40°)$ were taken from [11, 12].

2. Let us analyze the results of our measurements of the angular dependence $T_{b\lambda}(\theta)$ for the sea surface which are shown in Figure 6. To do this, let us begin first of all by comparing the data obtained with the results of calculations in the measurements presented in [9, 10].

It should be mentioned in this regard that in correcting the measurements of $T_{b\lambda}(\theta)$ from an aircraft or an artificial Earth satellite, when the dimensions of the resolving spot on the surface of the sea are much greater than the average length of the sea wave, there is a statistical averaging over the entire group of slopes for the sea surface.

In the case where $T_{b\lambda}(\theta)$ is measured from aboard a ship, and the dimensions of the resolving spot on the surface of the sea are less than or comparable to the average length of the ocean wave and the time constant of the radiometer is less than the average period of the sea waves, there is a variation in $T_{b\lambda}$ which is caused by changes in θ with time. Inasmuch as the averaging over the entire group is equivalent to averaging over the time by virtue of the stationary nature of the waves on the sea, the data from measurements of $T_{b\lambda}(\theta)$ with different spatial resolutions can be compared by introducing appropriate time averaging. As was indicated by measurements and calculations [8, 13], the function of the distribution density of the probabilities of the slopes for air /17 and ocean surfaces with waves as close to Gaussian and consequently determined by the average value $\bar{\alpha}$ and the scatter of slopes σ^2_θ. Hence, for a purely wind-produced wave condition the mean square value of the slope is linearly related to the wind speed U. This is explained by the fact that in the calculations in [9] which were carried out for wind produced waves the wind speed was selected as the parameter that governed the state of the sea surface. In carrying out our measurements, as a rule, we observed mixed types of waves; in many instances, there was a predominance of swells. It is clear that here it is necessary to use σ_θ and not the wind speed as the critical parameter for the state of the sea surface.

If the waves of the swell are represented in the form of regular sinusoidal or trochoidal waves, then as we know [14], the following will be valid for sinusoidal waves: $\sigma_\theta = \pi\sqrt{2 \times a/l}$, where a is the amplitude and l is the wavelength. For practical utilization of this relationship, taking into account the fact that the average height $\bar{h}$ and the average period $\bar{\tau}$ of ocean waves is known on the basis of hydrometeorological observations, let us express σ_θ by using $\bar{h}$ and $\bar{\tau}$. Taking into account the fact that $a = \bar{h}/2$ and using the known relationship $\bar{l} = g\bar{\tau}^2/2\pi$, we obtain the following equation: $\sigma_\theta = 1.43\overline{hs}/\bar{\tau}^2_\sigma$. A similar result is obtained for trochoidal waves, if $\pi\bar{h}/l << 1$. /18

For wind produced waves, we can also find the expression σ_θ by means of $\bar{h}$ and $\bar{\tau}$. The spectral theory of ocean waves we know [15] that $\bar{h} = \sqrt{2\pi\sigma_{h^2}}$ and $\bar{l} = 2\pi(\sigma h/\sigma\theta)$ where σ_h^2 is the scatter of the heights of the waves. Using the relationship between $\bar{l}$ and $\bar{\tau}$, we obtain the value of the projection of the mean square slope on the principal direction of propagation of the waves: $\sigma_r = 2.13\bar{h}/\bar{\tau}^2$. The value of the projection of σ_y on the perpendicular direction on the basis of the data in [13] may differ by σ_x by a factor of 2 to 3.

The scatter of the slopes of the sea surface in the case of mixed types of waves can thus be estimated by taking the sum of the scatters of the slopes for wind produced waves and waves produced by the swell.

In our case (Figure 6) the range of variations in $\sigma_{x,y}$ during measurements amounts to 0.6 to 0.175 radians and and all of the experimental points lie within the calculated curves corresponding to values of $\bar{\sigma}_\theta$ from 0 to 0.218 (U = 15 meters per second).

The relationship $T_{b\lambda}(\theta)$ for the sea surface upon the sounding angle with vertical and horizontal polarizations differ markedly. The value $T_{b\lambda}$ for vertical polarization in the vicinity of the altitude of -40° is practically independent of the state of the water surface. In the range of angles between -10 and 20°, on the other hand, there is a noticeable dependence between the /19 radio brightness temperature and the state of the sea surface, which leads to a decrease in $T_{b\lambda}$ as the intensity of the waves with vertical polarization increases, while with horizontal polarization there is an increase in $T_{b\lambda}$.

Hence, the results obtained on the angular dependence of $T_{b\lambda}(\theta)$ at different polarizations confirm the possibility of obtaining information on the temperature and the state of the sea surface on the basis of data from microwave measurements.

3. Samples of recording of the time variations $T_{b\lambda}$ and the reflected solar radiation, obtained on the 5th of September during sounding of the surface of the ocean at an angle of θ = -20° and the data from the wave recorder presented in Figure 7. Curve 1 corresponds to the vertical component of the radiation on the 2.5 cm wavelength, and curve corresponds to horizontal polarization on the 8.5 cm wavelength. The value $\partial T_{b\lambda}/\partial\theta$ with vertical polarization in the range of angles from -10° to -30° amounts to 2 to 4°K per degree, which is 2 to 3 times greater than $\partial T_{b\lambda}/\partial\theta$ for horizontal polarization and also differs in sign (see Figure 6).

Inasmuch as the amplitude of their slopes of the sea surface as a rule does not exceed 5 to 6°, the relationship $T_{b\lambda}(\theta)$ may be approximated by a broken line function and taken into account in the first approximation as follows: $\partial T_{b\lambda}/\partial\theta$ = const for each individual measurement. Then the time constant $\overline{T}_{b\lambda}(\sigma, t)$ may be represented in the following form:

$$\overline{T}_{b\lambda}(\theta, t) \simeq \overline{T}_{b\lambda}(\theta_0) + \partial\overline{T}_{b\lambda}(\theta_0)/\partial\theta\cdot\theta(t) \qquad (2.2)$$

/20

where θ_0 is the sounding angle, $\overline{T}_{b\lambda}(\theta_0)$ is the average brightness temperature of the sea surface with $\theta = \theta_0$, $\theta(t)$ is the projection of the slope in the direction determined by the angle between the principal direction of propagation of the waves and the sounding plane. Hence, it is possible to use the measurements of the $T_{b\lambda}(\theta, t)$ to proceed directly to an analysis of the time of variations of the slopes of the sea waves.

Figure 8a shows the frequency spectra of the projections of the slopes in the principal direction of propagation of the waves which were obtained by computer calculations on the basis of considerations presented in Figure 7 (curves 1 and 2), lasting approximately 10 minutes each. The frequency spectrum of the peaks obtained on the basis of data from the wave recorder measurements is shown in Figure 8b.

The scatter of the projections of the slopes calculated on the basis of the data from the spectra amounts to 0.0022 and 0.0014 rad^2 respectively on the 2.5 and 8.5 cm wavelengths, and the scatter of the heights of the waves is -0.3 m^2. The data obtained with horizontal polarization clearly must be viewed as a projection of the slope on the perpendicular direction relative to the principal direction of propagation of the waves.

An analysis of the spectra obtained with use of estimates in [15] has shown that the scatter of the projections of the slopes with respect to the β of the radiometric measurements in this case is reduced to approximately 10% due to the limited spatial resolution of the ceiling antennas. In order to reduce this error it is necessary to increase the resolving power of the radiometers by increasing the sounding angles for the same antennas are using receiving antennas with a narrower directional diagram. However, by increasing the sounding /21 angle one considerably decreases the coefficient $\partial \bar{T}_{b\lambda}(\theta_0)/\partial\theta$ in (2.2) and consequently the requirements for the sensitivity of the radiometer are increased as well.

4. Let us examine some of the results obtained concerning the radiation of the sea foam. A study of the characteristics of microwave radiation of natural sea foam which arises when the waves break unfortunately cannot be presented in adequate volume, inasmuch as the intensity of the waves during our measurements did not exceed 4 points on the scale as a rule. The value of the coefficient of coverage of the sea surface with foam ν on the basis of estimates performed by photography (see Figure 9) varied from 0.2 to 1.5%. The reflecting capacity of the sea surface may be represented in form [16]: $R_\lambda = R_\lambda^\circ(1 - \nu) +$

$+ \nu R_\lambda^*$ where R_λ^0 and R_λ^* are the coefficients of reflection of the smooth surface and the surface with foam, respectively. Then the estimate of the variations in $T_{b\lambda}$, caused by ν, will be

$$\delta T_{b\lambda} = \nu(R_\lambda^\circ - R_\lambda^*)[T_0 - \overline{T}_{atm}(\theta_0)] \tag{2.3}$$

where $\overline{T}_{atm}(\theta_0)$ is the mean brightness temperature of the atmosphere at an angle of θ_0. For the wavelength which we employed, the highest estimate of the value $\delta T_{b\lambda}$ with a four-point wave magnitude ($R_\lambda^* \simeq 0$) of the order of 1.5°K, which is significantly less than the variations in $\delta T_{b\lambda}$ caused by variations in the slopes: according to (2.2) these are equal to 3-10°K ($\sigma T_{b\lambda} = \partial \overline{T}_{b\lambda}/\partial\theta \cdot \sigma_\theta$). /22

Nevertheless, several estimates of the value of R_λ^* have been obtained on the basis of measurement results for foam which is formed during the breaking of the bow wave when the vessel is underway. Figure 10 shows a sample of a recording that was obtained on the 2.5 cm wavelength during sounding of the surface of the sea with the vessel underway at an angle of $\theta = -45°$. At the moments in time which correspond to the time marker indications, the surface of the sea was photographed using a narrow-angle objective having a field division approximately equal to the width of the radiometer beam (see Figure 11).

Let us estimate the value of R_λ^* by using expression (2.3) for moments in time marked in Figure 10 by numbers 1 and 2. The values that are included in (2.3) are respectively equal to the following: $\Delta T_{b\lambda} \simeq 118°K$, $R_\lambda^\circ = 0.503$, $T_0 = \overline{T}_{atm}(45°) \simeq 290°K$, $\Delta\nu = \nu_1 - \nu_2 \simeq 0.9$. We will then have: $R_\lambda^* = 0.05$. In order to obtain a spectral characteristic R_λ^* it is necessary to take into account the parallax between the optical axes of the radiometers and the optical axis of the camera which means that the value of ν at different values of λ will differ as a function of the lack of agreement between the spatial distribution of the foam over the surface of the sea.

5. Some of the results of microwave sounding of the atmosphere that were obtained in the first polygon (approximately 7.2°M, approximately 20.5°W and in the fueling area of the vessel (approximately 19°N, approximately 16.3°W) under various meteorological conditions, are shown in Table 2.3. The optical thickness

of the atmosphere τ_0 with $\theta = 90°$ was determined using the method of sectioning of the atmosphere by altitudes θ [17]. To estimate the degree of spatial inhomogeneity of the atmosphere, relationship $\tau_0 = f_\lambda(\text{cosec }(\theta_k - \theta_2))$ were plotted for each λ with θ_2 = const. Inasmuch as expression (3) was obtained for a flat-layered model of the atmosphere, only those values of τ_0 were analyzed which satisfy the equation $f_\lambda(\text{cosec }\theta_1)$ = const.

Separate determination of the absorption in water vapor τ_{H_2O} and clouds τ_{cloud} were derived by solving the system of equations of the following form: $\tau_0(\lambda k) = \tau_{O_2}(\lambda k) + \tau_{H_2O}(\lambda k) + \tau_{cloud}(\lambda k)$ where τ_{O_2} is the integral absorption in oxygen. The variations in τ_{O_2} in the microwave region are very small, so that the value of τ_{O_2} may be considered a constant and it is only necessary to solve the system with respect to τ_{H_2O} and τ_{cloud} [18]:

$$\tau_{cloud}(\lambda_1) = \frac{\tau_0(\lambda_2) - \tau_{O_2}(\lambda_2) - A[\tau_0(\lambda_1) - \tau_{O_2}(\lambda_1)]}{\left(\lambda_1/\lambda_2{}^2\right) - A} \quad (2.4)$$

Here $A \simeq \dfrac{\tau_{H_2O}(\lambda_2)}{\tau_{H_2O}(\lambda_1)}$, with the values $\tau_{O_2}(\lambda)$ being taken from [19-20]. The value of A according to the data from our measurements for a cloud-free atmosphere for the 0.8-1.6 cm and 1.35-1.6 cm wavelengths, corresponding to 1.11 ± 0.02 and 3.3 ± 0.4, respectively.

The total water content of the clouds W was found according to [18] as follows:

$$\overline{W}(\text{kg/m}^2) = \tau_{cloud} \cdot \lambda^2 \cdot 10^{1-0.012(290 - \overline{T}_{cloud})} \quad (2.5)$$

where $\overline{T}_{cloud}$ is the mean temperature of droplet clouds which radiosonde data indicated amounted to 15-18°C in the area where our measurements were made.

Determination of integral water content of the clouds having $W < 1$ kg/m^2 was carried out in this case on the basis of the results of sounding on the 0.8

and 1.6 cm wavelength, with $W > 1\ kg/m^2$, using the combination of the 1.35 and 1.6 cm wavelengths. The error in determining W for the clouds then depended primarily on the accuracy with which $\overline{T}_{cloud}$ was determined, and amounted to a figure on the order of 20%. /24

The total moisture content of the atmosphere was determined by means of a relationship which is given in [21]:

$$\overline{Q}\ (g/cm^2) = (12.5 \pm 0.8)\cdot\tau_{H_2O}(1.35) \qquad (2.6)$$

where

$$\tau_{1.35}^{H_2O} = \tau_{1.35}^{0} - 1.4\cdot\tau_{1.6}^{cloud} - 0.02$$

The value Q which is plotted in Table 2.3 agrees with the radiosonde data obtained aboard the vessel during the period of our measurements. It is necessary to mention in this respect a slight increase in Q from 14 to 20 July, clearly related to a change in the zone of convergence in the area of the measurements.

An example of the recording of the radio brightness temperatures of cumulonimbus clouds was obtained on the 0.8, 1.35, 1.6 and 3.4 cm wavelengths at a sounding angle of 12.5° on the 11th of July at a time that was close to the time that an aircraft was operating in the vicinity of our measurement area, shown in Figure 12. This same diagram shows the cross-sections of total water content of the clouds in the gaseous and liquid-droplet phases, which show that when the water content W changes by a factor of 3 (from 2 to 6 kg/m^2) the variations in Q amount to a figure on the order of 20%. We will assume that the increase in W at individual points in the section is accompanied by a decrease in the moisture content Q.

On the basis of these results we can draw the following conclusions. /25

1. Measurements of the angular dependence of the radiation from the sea surface with vertical and horizontal polarizations confirm the possibility of obtaining information on temperature and the state of the sea surface.

2. Measurements of the variations in radiation of the sea surface with waves with time make it possible to carry out remote studies of statistical characteristics of the waves on the sea from aboard a vessel.

3. Multiwave sounding of the atmosphere in the microwave range makes it possible to obtain detailed characteristics of the integral water content of the atmosphere in the gaseous and liquid-droplet phases.

4. The results of the experiments that were performed indicate that the theoretical possibility of carrying out microwave soundings of the atmosphere and the surface of the sea from aboard a vessel.

TABLE 1.4.

grad	-2	-4	-6	-8	-10	-15	-20	-30	-45	= -10
ε'	0.8	0.73	0.7	0.78	0.81	0.89	0.925	0.075	0.99	0.02
$\tilde{\varepsilon}_2$	0.97	0.963	0.936	0.938	0.943	0.945	0.968	0.983	0.99	0.016
$\tilde{\varepsilon}_1$	0.971	0.967	0.954	0.955	0.958	0.96	0.975	0.986	0.992	0.021
ε	0.202	0.362	0.489	0.591	0.672	0.800	0.888	0.958	0.984	

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